

A New Generation of Flexible and Adaptable Decision Making Tools for Resilient Infrastructures

Dr Sarah Dunn, Samuel Gonzalez Otalora, Joshua Jordan

School of Engineering
Newcastle University
Newcastle, UK
sarah.dunn@ncl.ac.uk

Abstract—Infrastructure systems (e.g. water, electricity, transport networks) are the main facilitator of a country's social, economic and environmental wellbeing, by providing access to healthcare, education and communications, to name but a few examples. However, in many worldwide communities these systems are currently being subjected to a multitude of challenges – from a changing climate, to increasing population demands and economic austerity. The individual components of infrastructure systems (e.g. roads, bridges, reservoirs) are constructed to have long asset lives and existing components were therefore not designed to cope with these ever increasing external pressures. As a consequence, the ability of our infrastructure systems to provide at least a baseline level of service after a severe weather event is being compromised. In many cases, particularly in the UK, current solutions to increase the resilience of infrastructure systems are based on an ad hoc procedure. This is mainly due to the current high levels of uncertainty regarding long-term climate projections, meaning that they cannot be reliably used as a basis for changing the design of future assets (e.g. through alteration of design codes), or to inform decisions to permanently alter current assets (e.g. through the construction of permanent flood defences). Within this current “period of flux” we cannot simply do nothing, nor can we base decisions upon such uncertain models, we therefore require alternate more “adaptive” solutions to increase the resilience of our infrastructure.

This paper will consider the development of a new generation of analysis and decision making tools, utilising deployable resources (e.g. mobile flood defences, grit storage) to increase the resilience of infrastructure systems when subjected to severe weather events. Using this solution, a baseline level of service to our communities can be ensured, either through the protection of individual assets or the provision of a temporary service, without the need of long-term climate scenarios to inform decisions. To ensure that this solution is effective, the main concern is the location of the deployable resource and also the timescale for deployment. This paper proposes, and tests, a decision making “tool”, which can be used to identify the most suitable location(s) for storing resources, so that they can be deployed, when and where they are needed, with minimised average and maximum travel times.

Keywords—resilience, infrastructure, disaster management, hazards

I. INTRODUCTION

Natural disasters are consequences of nature and can lead to loss of life and significant damage to local, and global, economies and infrastructure [1]. They can take various forms, including: meteorological events such as floods, hurricanes, droughts or geological activities such as earthquakes and volcanoes. These events are well renowned for their devastating impacts on civilisation and possess significant restraints on future development [2]. The initial impact of a natural disaster can be prolonged and amplified by disturbances to critical infrastructure systems, such as: electrical networks, water systems and transportation systems. Failures in critical infrastructure systems often intensify the natural catastrophe and can lead to a significantly increased death toll [3].

It is often the failure to understand these complex, interacting infrastructure systems, to which our modern communities rely for “normal” everyday service, which lead to disproportionate impacts when they are disrupted by hazard [4]. For example, in the aftermath of hurricane Katrina two dozen hospitals were left without electricity, meaning that they could not operate laboratory and x-ray equipment, dialysis machines and ventilators, resulting in many potentially preventable deaths [5]. The effects of a natural disaster can also be felt economically and this economic disruption can linger for a significant period of time after the event. For example, the estimated damage of the 2011 Tohoku earthquake and tsunami (Japan) is around \$185-\$309 billion [6] and has been estimated at five, or more, years to rebuild [7]. This estimated cost does not include the effects of power outages, caused by the nuclear crisis at the Fukushima power plant, or the subsequent loss of revenue to businesses.

In our current uncertain climate, many natural hazard events have been predicted to either increase in frequency (impacting our communities more often) or in intensity (creating larger impacts). It is therefore, becoming increasingly important that we understand the role that critical infrastructure plays with regards to society, that we are able to understand the implications for infrastructure failures and that we develop methods to form effective disaster management plans in order to mitigate against these failures. In order to be effective, these

disaster management plans need to be in place prior to a natural hazard event, meaning that information regarding potential infrastructure failures needs to be simulated data, rather than observed data. There currently exist a number of methodologies in order to obtain this information, some of which have associated probabilities, giving a level of certainty to any predictions. The discussion of these methodologies is outside the scope of this paper; however, the reader is directed to studies using: network graph techniques [8, 9], catastrophe risk modelling techniques [10, 11] and traditional physically based modelling approaches [12], for further information. Coupling this uncertainty in infrastructure system performance after a disaster event, with the increasing complexity of our cities, increasing urbanisation and a changing climate, creates a very complex problem.

However, what is almost certain is that after a major natural disaster event there will be damage to critical infrastructure systems and consequently a loss of service. In the immediate post-disaster period backup systems are often used to compensate for service loss (e.g. electricity generators or water trucks). The locations for these services need to be carefully considered, in order to minimise the travel time from where they are stored to where they are needed, so they can be accessed and mobilised quickly when needed.

In this paper, we develop a method to effectively locate resources prior to a natural hazard event, in order to minimise the distance to where they are needed in the immediate post disaster period. We incorporate a “risk” element into our analysis, allowing sites/assets that either have a higher risk, or high consequence of failure, to “pull” the location of resource closer (allowing for a reduced distance). We also conduct a sensitivity analysis of our presented methodology.

II. DISASTER MANAGEMENT CYCLE

Disaster management can be considered to be “*the organisation and management of resources and responsibilities for dealing with all humanitarian aspects of emergencies*” [13]. The risk of natural disasters will always be present in society and therefore infrastructure owners and operators, local and regional governments need to be prepared to handle emergency situations that may arise. This requires the coordination of emergency plans of various organisations. Warfield [14] outlines the three aims of disaster management to be to: (i) reduce, or avoid, losses from hazards, (ii) assure prompt assistance to victims, and (iii) achieve rapid and effective recovery. These aims broadly detail the components of the disaster management cycle, providing effective targets in minimising damages to communities in the event of a disaster.

The disaster management cycle, demonstrated in Fig. 1, commonly consists of four phases [15, 16]. These are often split into two categories: pre-disaster (mitigation and preparedness) and post-disaster (response and recovery), although mitigation can also fall into the latter. It is a continuous process by which lessons are learnt from each

individual disaster and measures are then applied to alleviate adverse effect reoccurring, as a result of future disasters. In this paper, we are focusing on methods to assist in the preparedness phase of the disaster management cycle, in order to be implemented during the response and immediate recovery phases.



Fig. 1. Showing the four phases of the disaster management cycle, adapted from [17].

III. POTENTIAL IMPACT OF CORRECTLY LOCATING RESOURCES

The identification of probable resource requirements, and their most effective storage location, is a key factor in managing potentially catastrophic situations, as well as protecting critical infrastructure whilst reducing fatalities [18]. In many previous natural hazard events, planning where to locate vital resources could have significantly aided throughout the aftermath and recovery efforts. It is worth noting that these emergency resources could be those that communities require in the pre-disaster period (e.g. flood defences) or in the immediate post-disaster period (e.g. shelters, healthcare).

In the case of resources required in the pre-disaster period, even for natural hazards with limited warning times (e.g. tsunami or hurricane), the effective location of these resources could significantly reduce negative social and economic impacts. However, it should be noted that it is not enough just to locate the resources effectively, there also needs to be a clear protocol in place for their use and deployment [19].

Effectively locating resources within a supply chain can have a tremendous return in the event of a crisis. Hale and Moberg [20] state a four-stage process to effectively locate emergency resources:

- 1) Identify the resources needed at each location
- 2) Identify the critical facilities within the supply chain
- 3) Set a maximum response time for access to emergency resources and a minimum distance of a site storage area that must be placed away from the supply chain facilities.

To date, only a limited amount of research has been conducted regarding the positioning of emergency resources and in order to ensure any disaster management protocol can be deployed, the positioning and response time is critical.

Hence, emergency logistical planning can be established if policy makers can visualise and map how responsive their resources are, in turn, creating a situation where with enough warning time infrastructure can be protected and then utilised to reduce the impacts of the aftermath [21].

IV. EMERGENCY RESOURCE LOCATION METHOD

In this paper, we develop a methodology for resource placement based upon the “weighted geographic centre” theory. The geographic centre of a set of coordinates, points, locations can be found by averaging their x-coordinate and y-coordinates. Whereas, the weighted geographic centre is an adjusted geographic centre based on the attribute associated with each point (see Fig. 2). This weighting could represent the ‘importance’ of a location to a user group (e.g. size of asset, greater quality of product) or could represent the probability of failure for each asset, for example. The weighting essentially allows point with a higher weighting have more “pull” on the weighted centre moving it closer towards that point. For a detailed overview of this method, the reader is directed to [4]. Whilst this may seem like a fairly straightforward calculation, there are a number of factors that need to be taken into account in this ‘weighting’ and also an appreciation of how this value impacts on the location of the weighted geographic centre. For example, in the case of a hazard risk to these points, is this weighting made directly proportional to the risk or is there a magnification factor that should be considered.

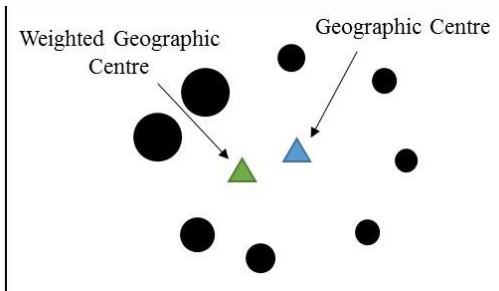


Fig. 2. Showing a series of points (black dots) where the size of the point indicates their “importance” (larger points being more important). The geographic centre is shown as a blue triangle, and the weighted geographic centre as a green triangle.

V. CASE STUDY: UK FLOOD HAZARD

Flooding is perhaps the most disruptive and most likely natural hazard to impact the UK. The floods in the summer of 2007 showed the geographically widespread nature of many natural hazards, with surface water flooding affecting many towns, villages and individual properties from Bristol to Newcastle. This event also caused damage to a number of infrastructure systems, including the closure of electricity substations (including the closure of the Castle Meads substation which left 42,000 people without power for up to 24 hours, [22]) and water treatment works (including the closure of the Mythe water treatment works causing 350,000 people to be without access to mains water supply for 17 days

[23]) due to flooding. It was estimated that the insurance industry expected to pay out over £3 billion and economic losses to infrastructure systems was estimated at £674 million, with the water sector the worst affected [24]. After this flood event a detailed report was commissioned, the Pitt Review [25], which called for ‘a more systematic approach to building resilience in critical infrastructure’ [26] and highlighted the need for:

- Improved understanding of the level of vulnerability to risk to which infrastructure and hence wider society is exposed;
- More consistent emergency planning for failures;
- Improved sharing of information at a local level for emergency response planning.

Other recent notable flood events in the UK include the flooding in Cumbria in November 2009 (which notably ‘cut in half’ [27] communities through severe damage to bridges and also caused disruption to energy and water infrastructure [28]) and the summer 2012 floods (which included a flash flood event in Newcastle, where a month’s rainfall fell in two hours, causing major disruption to transport infrastructure). In a recent report, the Environment Agency highlighted that there were ‘significant risks to important national infrastructure’ [29] as a result of flooding; with over 55% of water and sewage pumping station/treatment works, 20% of railways, 10% of major roads, 14% of electricity and 28% of gas infrastructure located in areas at risk from flooding.

In this paper we use a flooding event as the cause of disruption and to determine the infrastructure either in need of protection (in the pre-disaster period) or access to resources in the immediate post-disaster period. To calculate the extent of the hazard for a case study area, we first obtained flood maps from the Environment Agency and coupled these with a district map of the UK, calculating the flood risk in each district (Fig. 3). It is worth noting that we consider any severity of flood hazard in this analysis, from high to very-low, we want to capture the total extent of flooding rather than considering the likelihood in this case.

VI. CASE STUDY: RESOURCE PLACEMENT

After assessing the extent of flood hazard in the UK, we now focus on one area as a case study for which to apply the methodology. In this example, the aim is to assess the sensitivity of the weighted geographic mid-point tool to the risk associated with a number of asset sites.

To achieve this, we have chosen a small area of the UK (approx. 100km square) to form our case study (Fig. 4). Within this area, we have identified the location of schools (2,166) and medical care facilities (410), which will act as the assets requiring a quantity of resource. It is worth noting, that we assume all assets require the same quantify of resource. We have also calculated the extent of the flood hazard in the area, and used this to determine the number of assets at risk of flooding. We carry out three analysis, the first calculating an unweighted geographic centre, the second assigning those assets at risk of current flood predictions a higher “weighting”,

and the final analysis considering those assets within a 1,500m distance of the current flood hazard to have the higher “weighting” (to assess how a changing climate may impact the results achieved).

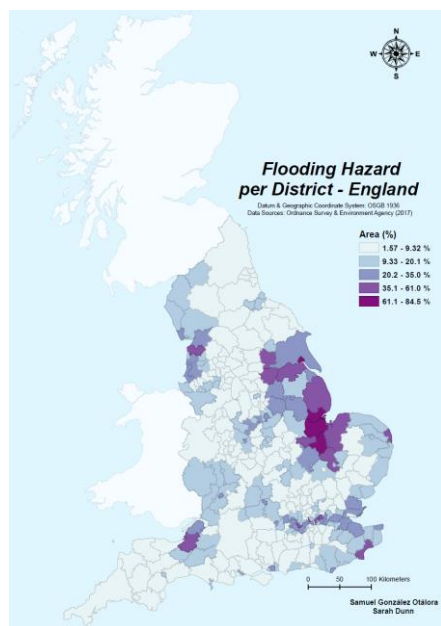


Fig. 3. Showing total area covered by a flood hazard for UK districts

The initial calculations for unweighted geographic centre, for both schools and medical care facilities, are shown in Fig. 4 and Fig. 5. It can be seen that the geographic centres for both case studies are very close to the centre of the case study region, due to the spreading of assets over the location.

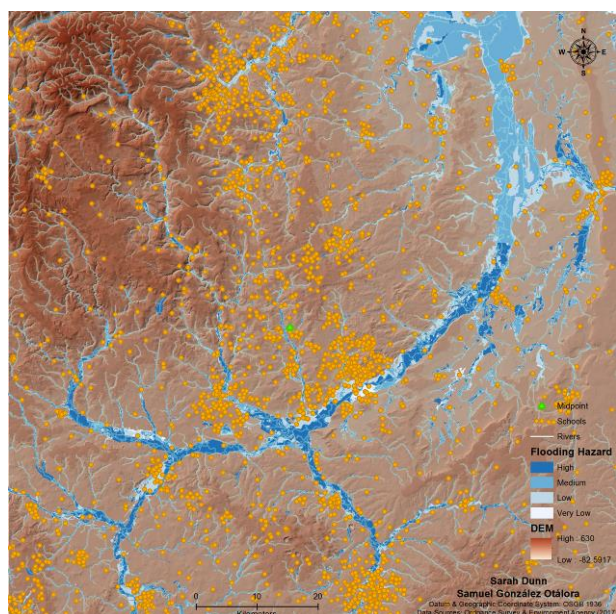


Fig. 4. Showing the location of assets (schools) in a case study area within the UK (orange dots). The geographic centre is indicated by the green triangle. The topography of the area is also shown, as is the extent of the flood risk (blue areas).

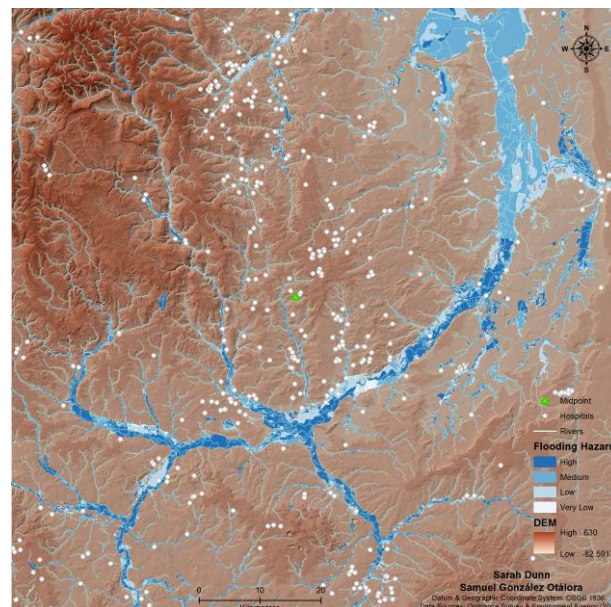


Fig. 5. Showing the location of assets (medical care facilities) in a case study area within the UK (white dots). The geographic centre is indicated by the green triangle. The topography of the area is also shown, as is the extent of the flood risk (blue areas).

We then identify those assets (both school and medical care) at current flood risk, which are highlighted in Fig 6 and Fig 7. There are 129 schools at current flood risk (approx. 6% of all schools) and 29 hospitals at current flood risk (approx. 7% of all medical care facilities). We assign different “weighting” values to the sites at flooding risk and assess how the location of the geographic centre “moves” with this analysis. These increased weightings allow the flood risk sites to “pull” the geographic centre, and therefore location of resource, closer to themselves. We undertake the analysis to assess how the location and “strength of pull” that each flood risk site has impacts the location of the resources. The results of this analysis are shown in Fig 6 and Fig 7.

From these results, it can be seen that the location of the weighted geographic centre for schools moves in a south-easterly direction as the “weighting” assigned to schools at risk of flooding increases. Whereas, the weighted geographic centre location for the medical care facilities assets moves in an easterly direction. Both of these are due to the location of the assets at flood risk.

Fig 8 and Fig 9 plot the weighing assigned to assets at flood risk, against the change in distance from the unweighted geographic centre to the resulting weighted geographic centre. The results in both of these figures are fitted with a logarithmic trend line, meaning that for small increases in the weighting assigned to risk assets there is a significant change in the location of the geographic centre (and therefore the location of resources). However, as this weighting is increased the impact to the location of the weighted geographic centre becomes less, eventually reaching a near static point.

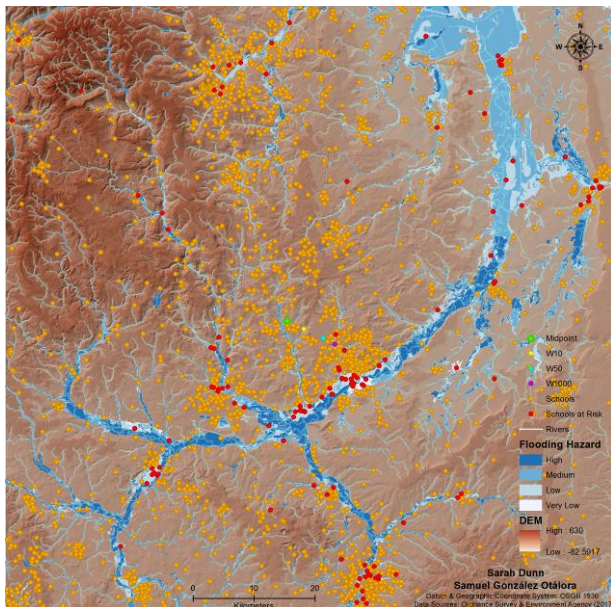


Fig. 6. Showing the location of assets (schools) in a case study area within the UK not at current flood risk (orange dots) and at risk of flooding (red dots). The geographic centre is indicated by the green triangle and the weighted geographic centres are indicated by the coloured dots. The extent of the flood risk is also shown (blue areas).

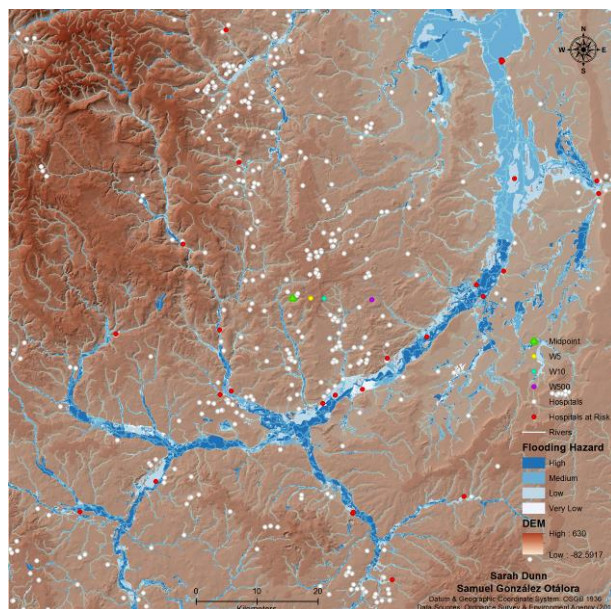


Fig. 7. Showing the location of assets (medical care facilities) in a case study area within the UK not at current flood risk (white dots) and at risk of flooding (red dots). The geographic centre is indicated by the green triangle and the weighted geographic centres are indicated by the coloured dots. The extent of the flood risk is also shown (blue areas).

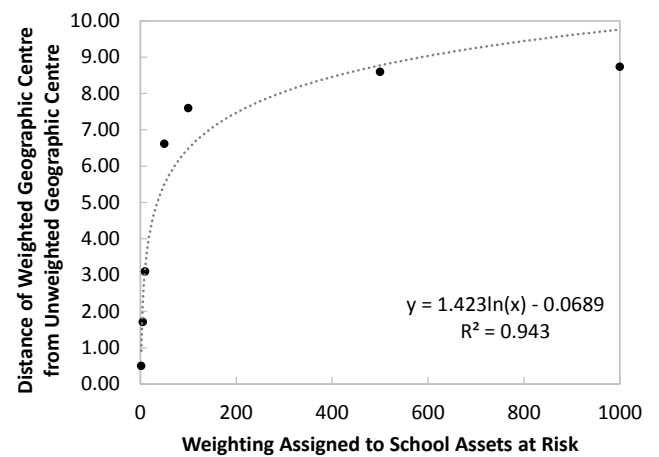


Fig. 8. Plotting the weighting assigned to school assets at risk of flooding and the resultant change in the distance of the weighted geographic centre from the unweighted geographic centre.

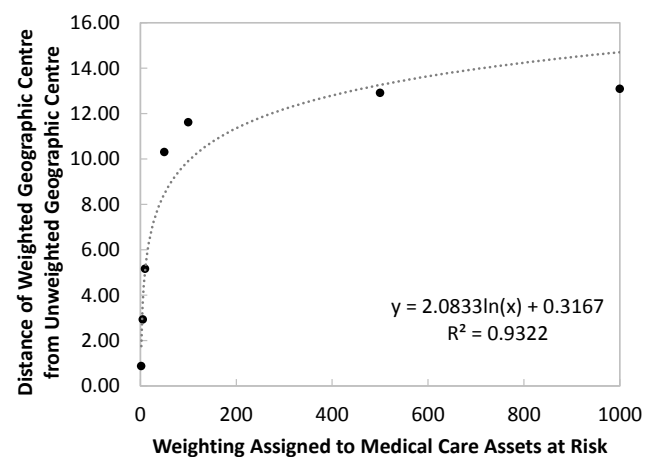


Fig. 9. Plotting the weighting assigned to medical care assets at risk of flooding and the resultant change in the distance of the weighted geographic centre from the unweighted geographic centre.

Finally, we assess how a potential increase in flood risk for the case study area will impact on the location of the weighted geographic centre, and therefore storage location of resources. To achieve this, we calculate the number of assets (schools and medical care) that are within 1,500m of the current flood risk boundary, as shown in Fig 8 and Fig 9. In this analysis, there are 2028 schools now at risk (approx. 94%) and 387 medical care facilities now at risk (approx. 94%). The results of this analysis are summarised in Table 3 and Table 4. It is worth noting that the value of 1,500m is arbitrary and not an indication of how climate changes may alter the flood risk within the case study area.

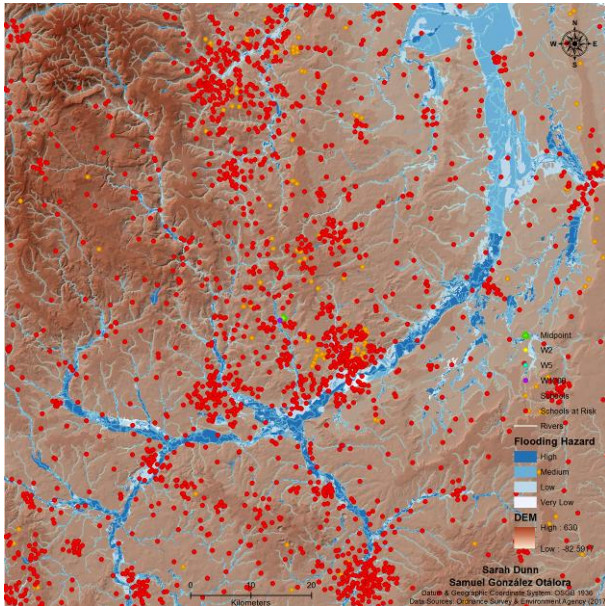


Fig. 8. Showing the location of assets (schools) in a case study area within the UK not at current flood risk (orange dots) and those within 1500m of current flood risk (red dots). The geographic centre is indicated by the green triangle and the weighted geographic centres are indicated by the coloured dots. The extent of the flood risk is also shown (blue areas).

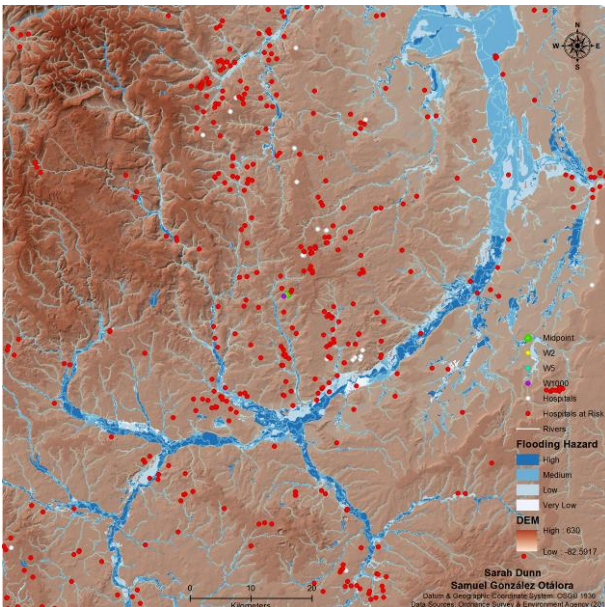


Fig. 9. Showing the location of assets (medical care facilities) in a case study area within the UK not at current flood risk (white dots) and those within 1500m of current flood risk (red dots). The geographic centre is indicated by the green triangle and the weighted geographic centres are indicated by the coloured dots. The extent of the flood risk is also shown (blue areas).

Table 3. Detailing the change in distance from the unweighted geographic mid-point when the schools within 1,500m of current flood risk are assigned a higher weighting.

Weighting	Distance from unweighted geographic mid-point
2	391 meters
5	639 meters
1000	808 meters

Table 4. Detailing the change in distance from the unweighted geographic mid-point when the medical care facilities within 1,500m of current flood risk are assigned a higher weighting.

Weighting	Distance from unweighted geographic mid-point
2	285 meters
5	464 meters
1000	586 meters

For both of these case study examples, it can be seen that the location of the weighted geographic centre does not alter by a large amount in relation to the location of the unweighted geographic centre. This is due largely to the large number of assets at flood risk in the case study, and also the distributed locations of these assets.

VII. CONCLUSIONS

In this paper, we have assessed the sensitivity of a weighted geographic centre tool to assets with differing associated risks. We applied our analysis to school and medical care assets in one case study location, assigning increasing weighting values to assets at flood risk. Through this analysis, it was found that there is a logarithmic relationship between the weighting assigned to assets and the change in location (in terms of distance) from the weighted geographic centre to the unweighted geographic centre. This suggests that just a small increased weighting value assigned to assets at risk of hazard will have a potentially large impact on the location of the weighted geographic centre and therefore the location of resources.

In this paper we have chosen to apply our analysis to that of medical care facilities and schools subjected to flood hazard. However, we could equally have chosen another form of hazard and an appropriate hazard model to determine the infrastructure assets most at risk. For example, in the case of wind storm hazard the assets closest to the center of the storm would be assigned the higher weighting (allowing them a greater "pull" on the weighted geographic centre and therefore moving the required resource closer to these points).

We have focused primarily on the distance from each asset location to the stored resource location (which is determined in the analysis). However, future studies should also consider the time taken for the stored resource to reach the asset location. This could be achieved by coupling the analysis to a road network dataset and running an optimisation algorithm.

Thereby, optimising the location of the resource (in a location close to the road network) so as to minimise the travel time, rather than distance, to each asset location. Through this analysis it may be that two, or more, sites result from the algorithm, due to the configuration of the road network (e.g. one route might be shorter, but use roads with a lower speed limit and a second route may be longer but use roads with a high speed limit).

ACKNOWLEDGMENT

Paper submitted to CESUN Conference 2018 (Toyko). This work was supported by the Engineering and Physical Sciences Research Council (EPSRC) for funding this research, under Grant EP/P02369X/1, we gratefully acknowledge their support.

REFERENCES

- [1] Munich Re Group, "Annual Review: Natural Catastrophes 2004" *Munich Re Group Knowledge Series*, 2005.
- [2] Awange, J., "Disaster management". 1 ed. Perth: *Springer International Publishing*, 2018.
- [3] Oral, B. & Dönmez, F., "The Impacts of Natural Disasters on Power Systems: Anatomy of the Marmara Earthquake Blackout", *Acta Polytechnica Hungarica*, 7(2), pp. 107-118, 2010.
- [4] Dunn S., "An Investigation to Improve Community Resilience using Network Graph Analysis of Infrastructure Systems", *PhD Thesis, Newcastle University*, February 2014.
- [5] Gray, B. H. and Herbert, K., "After Katrina: Hospitals in Hurricane Katrina - Challenges Facing Custodial Institutions in a Disaster", 2006.
- [6] Censky, A., "Japan Earthquake Could Cost \$309 Billion." Retrieved 13 October 2011, from http://money.cnn.com/2011/03/23/news/international/japan_earthquake_cost/index.htm, 2011.
- [7] Amadeo, K., "Impact of Japan's Earthquake on the Economy." Retrieved 7 October 2011, from <http://useconomy.about.com/od/criticalissues/a/Japan-Earthquake.htm>, 2011.
- [8] Dunn, S., Fu, G., Wilkinson, S. M., and Dawson, R., (2013) 'Network Theory for Infrastructure Systems Modelling' *Proceedings of the ICE – Engineering Sustainability*. 166(5): 281-292.
- [9] Dunn, S., and Wilkinson, S. M., (2012) 'Identifying Critical Components in Infrastructure Networks using Network Topology' *ASCE Journal of Infrastructure Systems*. 19(2): 157-165.
- [10] Dunn, S., Wilkinson, S. M., Alderson, D., Fowler, H., and Galasso, C., (2018) 'Fragility curves for assessing the resilience of electricity networks constructed from an extensive fault database' *Natural Hazards Review*. 19(1).
- [11] Pregolato, M., Ford, A.C., Glenis, V., and Dawson, R.J. (2017) "Impact of Climate Change on Disruption to Urban Transport Networks from Pulvial Flooding". *Journal of Infrastructure Systems* 23(4).
- [12] Novak, P., Guinot, V., Jeffrey, A. and Reeve, D. E. (2010). *Hydraulic Modelling - An Introduction: Principles, Methods and Applications*. 1st Edition. London and New York, Spon Press.
- [13] IFRC, 2015. *About Disaster Management*. [Online] Available at: <http://www.ifrc.org/en/what-we-do/disaster-management/about-disaster-management/> [Accessed 28 December 2015].
- [14] Warfield, C., 2004. *The Disaster Management Cycle*. [Online] Available at: http://www.gdrc.org/uem/disasters/1-dm_cycle.html [Accessed 28 December 2015].
- [15] Godschalk, D. et al., 1999. *Natural Hazard Mitigation: Recasting Disaster Policy and Planning*, Washington DC: Island Press.
- [16] Khan, H., Vasilescu, L. G. & Khan, A., 2008. *Disaster Management Cycle - A Theoretical Approach*, s.l.: s.n.
- [17] Alexander, D., 2000. *Confronting Catastrophe*. 1st Edition ed. New York: Oxford University Press.
- [18] esri, Public Saftey, 2017. *Emergency and Disaster Management*. [Online] Available at: <https://www.esri.com/en-us/industries/public-safety/segments/emergency-management> [Accessed 06 12 2017].
- [19] Society for Human Resource Management, 2017. *Managing Through Emergency and Disaster*. [Online] Available at: <https://www.shrm.org/resourcesandtools/tools-and-samples/toolkits/pages/managingemergencyanddisaster.aspx> [Accessed 06 12 2017].
- [20] Hale, T. & Moberg, C., 2006. Improving supply chain disaster preparedness: A decision process for secure site location. *International Journal of Physical Distribution & Logistics Management*, 35(3), pp. 195-207.
- [21] Wang, J., Haoxiong, Y. & Zhu, J., 2012. A Two-stage Stochastic Programming Model for Emergency Resources Storage Region Division. *Systems Engineering Procedia*, 5(2), pp. 125-130.
- [22] Cabinet Office (2008c). *The Pitt Review: Learning Lessons from the 2007 Floods*. Cabinet Office. London.
- [23] Environment Agency (2010a). *The Costs of the Summer 2007 Floods in England*.
- [24] OFWAT (2007). *Water and sewerage services during the summer 2007 floods*.
- [25] Cabinet Office (2008c). *The Pitt Review: Learning Lessons from the 2007 Floods*. Cabinet Office. London.
- [26] Cabinet Office (2011a). *Keeping the Country Running: Natural Hazards and Infrastructure (For Consultation)*. Cabinet Office. London.
- [27] Met Office (2012). "Heavy Rainfall / Flooding in the Lake District, Cumbria – November 2009". Retrieved 9 August 2013, from : <http://www.metoffice.gov.uk/climate/uk/nov2009>.
- [28] The Guardian. (2010). "Cockermouth, a year on from the floods." Retrieved 9 August 2013, from <http://www.theguardian.com/society/2010/nov/16/cockermouth-cumbria-floods-first-anniversary>.
- [29] Environment Agency (2009). *Flooding in England: A National Assessment of Flood Risk*.